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Connecting biology with psychology to make sense of appetite control

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Abstract

Eating more than is required to maintain bodyweight is weakly resisted physiologically, as appetite does not closely track body energy balance. What does limit energy intake is the capacity of the gut to accommodate and process what is eaten. As the gut empties, we are ready to eat again. We typically refer to this absence of fullness as 'hunger', but in this state, even when it is prolonged (*e.g.* by missing one or two meals), our mental and physical performance is not compromised because body energy stores are mobilised to sustain energy supply to our brain and muscles. We illustrate this by discussing research on the effects of missing breakfast. Contrary to conventional wisdom, it appears that missing breakfast leads to a reduction in total daily energy intake and does not impair cognitive function (in adequately nourished individuals). The problem with missing a meal or eating smaller meals, however, is that we miss out on (some of) the pleasure of eating (food reward). In current studies, we are investigating how to offset the reduced reward value of smaller food portions, by, for example, altering flavour intensity, food variety and unit size, in order to maintain overall meal satisfaction and thereby reduce or eliminate subsequent compensatory eating.

Keywords: breakfast, food reward, fullness, hunger, meal satisfaction, portion size

Introduction

We hardly need reminding that eating frequently in excess of energy requirements poses major health challenges. Our purpose here is to discuss why human beings are vulnerable to overeating and how that vulnerability might be reduced both individually and collectively. In this, our perspective differs somewhat from the common assertion that overweight and obesity represent a failure of energy balance 'regulation'. The observation that bodyweight can remain

very similar from one year to the next is not evidence that bodyweight is actively regulated, because this constancy is to be expected if a person's lifestyle, environment and physiology remain stable (*e.g.* de Castro 1996; Rogers 1999). Change one or more of those parameters, and weight is vulnerable to change, as happens for example after leaving home for university, after marriage and after migration (Ravussin *et al.* 1994; de Castro 1996; Levitsky *et al.* 2004). Instead, we argue that, whilst appetite is related to what was eaten recently (mainly at the last meal), it is only weakly influenced by overall energy balance. Although this makes humans liable to eat in excess of energy expenditure, it also implies that there is considerable scope to intervene to reduce energy intake.

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Appetite and energy balance

We have argued elsewhere (Rogers & Brunstrom 2016) that appetite *control* is only 'loosely coupled' with metabolic *regulation*. What we mean by this is that appetite does not closely track changes in energy balance. In part, this is obvious, in that energy intake happens in discreet bouts (meals and snacks), whilst energy expenditure is continuous, albeit with peaks during intense physical activity. However, more than this, our argument is that at any particular moment, appetite is very little affected by current energy balance, but is instead dominated by what was eaten most recently (and the attractiveness of the food currently on offer). This is because, even for a lean person, bodily energy stores are very substantial (Table 1) and energy supply to the body's tissues and organs is maintained whether or not a meal has just been taken (Frayn 2010). So in respect of energy balance, missing a meal or even several meals has a trivial effect. In contrast, consuming a meal is a significant physiological event requiring variously the digestion, absorption, utilisation, storage and excretion of the ingested constituents. Consequently, food intake has a large inhibitory effect on appetite. In other words, irrespective of the current state of body energy stores, the rate of energy intake is limited by the capacity of the gut to contain and process what is ingested. On the one hand, energy (nutrient) intake is necessary to maintain body function, whilst on the other, it presents an acute physiological challenge (Woods 1991).

Based on these considerations, we suggest that when a well-nourished person says they are 'hungry', they are not doing so in response to energy depletion, but instead because they have an empty or mostly empty stomach and upper gut, and, in that

state, eating is particularly rewarding (pleasurable). In other words, this self-reported hunger is really the absence of fullness together with the anticipation of food reward (Rogers & Hardman 2015). This is why we prefer the term appetite over hunger to refer to the motivation to eat where nutrition is adequate. In Dutch, 'Ik heb trek', meaning 'I have appetite', is a common phrase. If a Dutch child says 'Ik heb honger' (I'm hungry), they are likely to be told, at least by older Dutch people, 'no you are not, that's what people in a famine feel'. In English, the equivalent might be 'I'm hungry' compared with 'I'm starving'. Only the latter might be admonished as exaggeration. The use of language matters here because the mental model implied by 'hunger' potentially hinders attempts to eat less when this is desirable. Thus, despite more than adequate energy reserves, we may feel that food restriction will, for example, cause us to feel impossibly hungry or to 'run out of energy' so that we will not any longer be able to perform mental or physical tasks adequately. A realignment of these beliefs to reflect the biological reality of appetite control could assist with healthy weight management. Below we discuss two specific examples where this might be applied.

Missing a meal, including missing breakfast

Surely, we should not be advocating missing 'the most important meal of the day'. Well actually, this discussion is relevant to deliberately missing a meal or snack at any time of the day. Missing a meal on some occasions can be expected to result in reduced overall energy intake without the need to restrict intake (*i.e.* without eating less than is desired) at scheduled meals. In other words, this approach, in contrast for example to 'calorie counting', avoids the constant restraint of intake, which is both psychologically demanding and liable to disinhibition (Rogers 1999; Rogers & Brunstrom 2016).

It is the case that missing breakfast is associated with being overweight and obese (Brown *et al.* 2013) and that children who miss breakfast perform less well academically (Littlecott *et al.* 2016). However, it does not follow that eating breakfast will make us thinner or smarter. Intervention studies have shown little or no effect of missing breakfast on cognitive function in well-nourished children (Hoyland *et al.* 2009), even comparing, for example, 18 vs. 3 hours without food (Pollitt *et al.* 1981). This should be no surprise as, over the day, and irrespective of recent food consumption, the brain will be adequately supplied with

Table 1 The body's energy stores far exceed energy intake in a single meal and over a whole day*

For a lean, moderately active person
Total energy stored in the body is about $75 \times$ daily energy intake/ expenditure [†]
Fat = $55 \times$ daily energy intake
Protein = $20 \times$ daily energy intake [‡]
Carbohydrate = less than $1 \times$ daily energy intake
(Glycogen = 18 hours)
(Free glucose = 30 minutes)

*Based on Frayn 2010.

[†]Assumes intake and expenditure are in balance.

[‡]No more than 20% body protein can be utilised without serious adverse consequences.

glucose mobilised if necessary from glycogen stored in the liver and/or via gluconeogenesis (Frayn 2010; Table 1). In contrast, the short-term effect of food ingestion might be to impair cognitive performance, as certainly occurs after a large meal (*e.g.* Craig & Richardson 1989). We even found that a modestly sized breakfast (600 kcal; Rogers *et al.* 2013; Fig. 1) impaired memory and psychomotor performance. In fact, this effect of eating may well explain why breakfast, despite coming after the longest 'fast' of the day, tends to be a relatively small meal. Rather than being responsive to short-term fluctuations in energy balance, our meal pattern is adapted to minimise the acute disruptive effects of food intake on performance at work and at school (Rogers & Brunstrom 2016). It seems clear that adverse effects on cognitive performance of missing a meal, or indeed even longer periods of food restriction (Green *et al.* 1995; Benau *et al.* 2014), are at most minimal and should not be a cause for concern. The explanation for the association between breakfast consumption and performance in school probably lies in residual confounding, breakfast being a particularly good marker for a child's home circumstances and perhaps also for their and their caregivers' aspiration for educational achievement (Rogers 2016).

As for the robust correlation between missing breakfast and body mass index (BMI), reverse

causation, namely that being overweight prompts people to miss breakfast in an ultimately unsuccessful attempt to lose weight, is highly plausible. When dieting to lose weight, the start of a new day provides an opportunity to reaffirm the intention to eat less ('today I'm going to be good'). Missing breakfast represents an immediate realisation of that goal but at any point, subsequently, there is a risk that eating more than intended will cause the goal to be abandoned (Stroebe *et al.* 2013). This risk is likely to be increased if the individual is, for example, stressed or tired. Furthermore, overeating late in the day may, in turn, contribute to reduced appetite for breakfast, due to food remaining in the gut from late evening food intake, further reinforcing the correlation between missing breakfast and obesity. Again, however, this is not because missing breakfast causally increases the risk of obesity.

So what is the evidence on effects on energy intake and bodyweight from intervention studies comparing eating breakfast with missing breakfast? For energy intake, the results are very clear in showing that total daily energy intake is reduced when breakfast is missed (Levitsky 2005; Levitsky & Pacanowski 2013; Betts *et al.* 2014; Chowdhury *et al.* 2016). Although in some studies, an increase in energy intake at lunch has been observed after missing breakfast, the increase was small and did not come close to compensating for

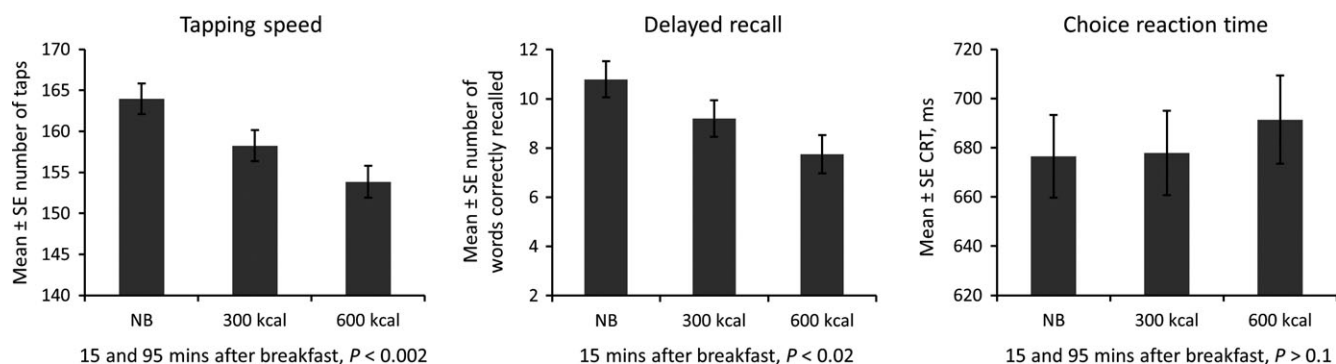


Figure 1 In this study, a total of 71 healthy adult participants (35 female) were tested in either a no-breakfast (NB), or 300 kcal or 600 kcal breakfast conditions (parallel-groups design). The purpose of using this design, rather than the more usual cross-over design, was to minimise the salience of the manipulation of food restriction. As a cover story, participants were told that the study was part of an investigation into circadian effects on performance and that they needed to consume the meal, or not eat, in order to control for effects of nutritional state on performance. Participants were randomly allocated to the three conditions, but were led to believe that their particular allocated condition was common to all participants. They performed a battery of three tasks lasting a total of 20 minutes immediately before (baseline) and starting at 15 and 95 minutes after breakfast/no breakfast. The breakfast food was a blended yogurt, cream and fruit meal (0.75 kcal/g), served either in a 400 g or 800 g portion. Breakfast was consumed within 10 minutes (9.15–9.25 am). Participants in the no-breakfast condition rested during this period. Water was available for participants to drink with the meal and during rest periods throughout the test session. The results shown are adjusted for performance at baseline. There was a 'dose'-related impairment of tapping speed (primarily a physical task) and memory performance (recall of a list of words presented 18 minutes earlier) following breakfast consumption. There was no effect of breakfast condition on choice reaction time (CRT; primarily a measure of speed of information processing). A summary of this study was presented at the 15th biennial meeting of the European Behavioural Pharmacology Society (Rogers *et al.* 2013).

the energy usually consumed at breakfast. Nor was there any further compensation later in the day (Levitsky 2005). These results can be fully understood by considering the physiological effects of missing vs. consuming breakfast. First, as described above, the effect on body energy balance is trivial (*cf.* Table 1). Second, within 3–4 hours after a meal, most of the food consumed will have been digested and the nutrients absorbed and utilised or assimilated into storage. Consequently, by lunchtime, an individual will be about equally not full (*i.e.* equally 'hungry') whether or not they ate breakfast (Fig. 2), although after eating a large breakfast, some residual fullness is likely to remain to reduce intake at lunch. Separately, memory of having eaten breakfast may contribute to the perception of fullness and to how much is consumed at lunch (Higgs 2002; Higgs & Donohoe 2011; Oldham-Cooper *et al.* 2011; Brunstrom *et al.* 2012). Nevertheless, by lunchtime, there is not much difference in overall physiological state between having eaten and not having eaten breakfast.

On balance then, missing breakfast ought to result in reduced bodyweight. Unfortunately, the evidence for this is mixed. In one study, participants randomised to miss breakfast lost more weight over

4 weeks than did participants randomised to consume either porridge or cornflakes for breakfast (Geliebter *et al.* 2014), but the majority of studies have not found a significant effect of missing vs. eating breakfast on bodyweight (Brown *et al.* 2013; Dhurandhar *et al.* 2014). The degree of control over the intervention differed substantially between the studies. The first study was a hospital-based investigation (Geliebter *et al.* 2014) with close scrutiny of the participants' eating behaviour. The study by Dhurandhar *et al.* (2014), by contrast, compared the effect of written instructions (reinforced through dialogue with participants) about eating healthily, which either included no specific instruction to eat breakfast or the instruction to eat breakfast or to miss it. Both these protocols are valid, the first type providing proof of principle (efficacy) and the second a test of its possible implementation in a public health setting (effectiveness). However, guaranteeing and adequately monitoring compliance with the study intervention are considerably more difficult in the latter situation. It follows from our earlier discussion that it is possible that adopting a model of eating based on 'hunger is the absence of fullness' rather than 'energy depletion' would assist in compliance with interventions that required missing a meal or intermittent food restriction.

Another reason why missing breakfast might be less effective than predicted from its effect on energy intake is that energy expenditure may be reduced. In a recent study, along with the expected proportionate reduction in diet-induced thermogenesis, physical activity was reduced when participants missed breakfast (Betts *et al.* 2014; Chowdhury *et al.* 2016). Why this should occur is unclear. The participants were not highly active individuals in the first place, so their activity should not have been limited metabolically, but there may have been behavioural compensation, for example, driven by wanting to 'conserve their energy' after missing breakfast.

Even when they are well-founded in relation to physiology, behavioural strategies for maintaining a healthy weight will ultimately fail if they are not felt to be acceptable or sustainable. One barrier to missing breakfast is the popular advice that it is the most important meal of the day, based in part on the mistaken interpretation of the correlation between missing breakfast and obesity (Brown *et al.* 2013). Updating that advice to be consistent with biological reality and with the evidence from intervention studies, as has been done, for example, in the recent National Institute for Health and Care Excellence (NICE) guidelines

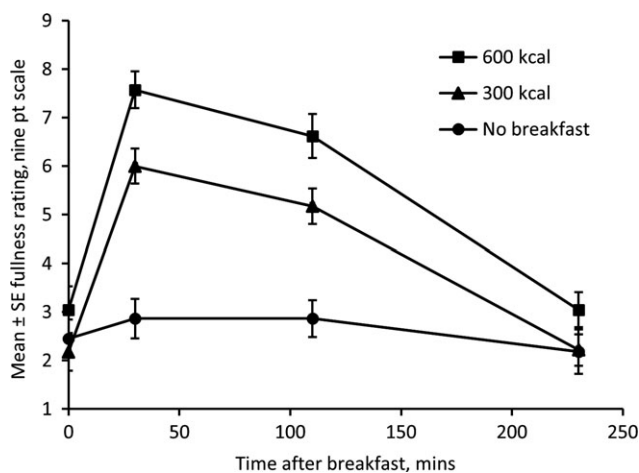


Figure 2 Fullness before (0 minutes) and after no breakfast, and 300 and 600 kcal breakfasts. These data are from the study described in Fig. 1. Fullness was rated on a nine-point scale, with one representing 'not at all full' and nine representing 'extremely full'. The final ratings were made at 1.15 pm, after the participants had left the laboratory but before they ate again. There was a significant meal condition by time interaction effect, $P < 0.0001$. Note that within 230 minutes of breakfast, fullness had returned to pre-breakfast levels and did not differ between the three conditions ($P > 0.1$). Geliebter *et al.* (2014) report a similar result. Hunger ratings showed the inverse pattern. Hunger and fullness after breakfast across the three conditions were highly correlated ($r = -0.80$, $P < 0.0001$).

on preventing excess weight gain (www.nice.org.uk/guidance/ng7/chapter/3-Considerations), might help change attitudes towards missing breakfast. However, a greater problem is that missing a meal requires that we deny ourselves the pleasure of eating and even if we manage to do this by, for example, missing breakfast, there is a risk that we will be tempted to eat relatively soon. This is because, without fullness to reduce food reward (Rogers & Hardman 2015), the prospect of eating remains attractive. In everyday language, we would explain this by saying that missing breakfast left us feeling 'hungry', but note, as discussed above, this is because missing breakfast has left us with an empty stomach and not because our body energy stores are low.

Overall, missing a meal can be expected to reduce daily energy intake, and this strategy might be more readily adopted and adhered to if it was framed in terms of the real challenge of eating less, namely missing out on some pleasure, rather than in terms of resisting hunger. In contrast to eating fewer meals, another strategy for reducing energy intake is to eat smaller meals by choosing smaller food portions. In the next section, we describe some current research on this topic. In this work, which is funded by Biotechnology and Biological Sciences Research Council (BBSRC) Diet and Health Research Industry Club (DRINC; see Acknowledgements), we are not advocating calorie counting by consumers, but rather the provision of smaller portions by industry, including food manufacturers and restaurant chains.

Reducing portion size without reducing meal satisfaction

There is ample evidence that food portion size affects how much is consumed (Ello-Martin *et al.* 2005; Hollands *et al.* 2015), and over 11 days, there is a cumulative effect when larger portions are served repeatedly (Rolls *et al.* 2007). We suggest that this occurs primarily because, as outlined above, there is no precise meal-to-meal energy balancing by the body (Rogers & Brunstrom 2016), coupled with a strong tendency in everyday life to eat the whole available portion, for example, the entire chocolate bar or all or almost all of the food on our plate (Geier *et al.* 2006; Fay *et al.* 2011; Hinton *et al.* 2013). Furthermore, portion sizes of many foods, including packaged foods, and foods served in restaurants and in the home, have increased since at least the 1970s (Nielsen & Popkin 2003). Therefore, reversing this trend could be expected to significantly reduce overall energy intake and thereby

lower the risk of overweight and obesity (Ello-Martin *et al.* 2005).

Of course, reducing portion size is far from simple in practice (Marteau *et al.* 2015). An obvious concern is the effect on consumers' perception of value for money, as there is little, if any, scope for reducing the retail price commensurate with the reduction in portion size. Another barrier to the effectiveness of reducing portion size is possible compensatory behaviour. At the extreme, a large reduction in portion size might cause the consumer to choose a double portion or add a supplementary item to their meal. Part of our research is investigating the limits of this by assessing consumers' ability to detect a difference between standard and reduced portion sizes in a variety of situations. For example, participants are asked to make judgements on portion size in a side-by-side comparison (*i.e.* which is larger?) or based on their memory of the standard portion presented earlier in the test session (McCaig *et al.* 2016). Not surprisingly, there is less sensitivity to portion size differences in the latter situation, but overall, the findings suggest that significant reductions in portion sizes could be achieved through 'stealth' (*i.e.* implementing successive small reductions in portion sizes). Furthermore, portion size reduction might be reinforced over time as smaller portions become the 'norm', in the same way that large portions have come to be perceived as normal (*cf.* Robinson *et al.* 2016).

Fundamentally, however, both the reward and the fullness associated with eating a food are reduced when portion size is reduced. This could lead to compensatory eating even where smaller portions are the norm. Moreover, if noticeably different portion sizes of similar products are on offer at a similar price, the consumer is very likely to opt for, and eat all of, the larger portion (unless the portion is in excess of an amount that can be eaten comfortably). Currently, we are investigating how to mitigate the reduced value of a smaller portion of food. One approach we considered is to add ingredients (*e.g.* non-starch polysaccharides) to increase the fullness of the smaller portion. Such ingredients, however, can adversely affect the sensory (eating) quality of the product. Moreover, increasing the fullness of a food may over time diminish rather than enhance its acceptability. This is because fullness itself is not rewarding. This has been demonstrated in studies on animals (Sclafani & Ackroff 2004) and is also supported by, for example, the inverse relationship between 'palatability' and the satiety index of foods (Holt *et al.* 1995). Satiety index is a measure of the fullness of a food per calorie,

so at the extremes, boiled potatoes have a high satiety index, whilst chocolate has a low satiety index. Furthermore, excessive fullness is of course clearly aversive, not pleasant. The reason that fullness is not rewarding is that the biological value of food lies in its energy and nutrient content, and fullness actually limits energy and nutrient intake. Thus, the attractiveness of energy-dense foods lies at least in part in their high energy-to-satiety (fullness) ratio (Rogers & Brunstrom 2016). Nonetheless, we suggest that for humans, the reward experienced during eating and the fullness experienced at the end of the meal together determine meal satisfaction. Moderate fullness will add to meal satisfaction, but excessive fullness causing discomfort will detract from meal satisfaction.

The approach we are taking then is to see whether the satisfaction gained from eating smaller food portions can be enhanced without increasing either their fillingness or energy density (if the goal is to reduce energy intake, there would be no advantage gained from reducing portion size but not total energy content). Our model is to compare the effects of consuming a standard meal, for example a sandwich and flapjack at lunch, vs. the same items reduced in size, vs. the same items reduced in size but enhanced in various ways. The enhancements will include increasing variety in the meal (two types of sandwich filling and two varieties of flapjack), increasing flavour intensity of the ingredients (*e.g.* a sandwich made with strong- vs. mild-tasting cheese) and altering 'unit size' (*i.e.* serving a food divided into several small pieces vs. one large piece). There is already good evidence that variety increases food reward. It does so by reducing 'sensory-specific satiety' which is the experience that the pleasure of eating a food diminishes as the meal progresses, whilst the attractiveness of other, uneaten foods remains high (Hetherington 1996). This is the basis of what is sometimes referred to as having a 'dessert stomach' – we feel full from (have lost interest in) the food eaten in the first course but are nonetheless able to find 'room' for dessert. When excess food is available, food variety increases intake (Hetherington 1996; McCrory *et al.* 2012). However, when a fixed portion is served, as is usual in everyday life, we predict that food variety will increase the enjoyment (reward) and therefore satisfaction derived from eating the meal, and in turn, that will reduce or eliminate the compensatory eating that would otherwise occur when portion size is reduced. Furthermore, because consumers are able to anticipate eating enjoyment (Wilkinson *et al.* 2013), we expect the varied meal to be more desired, which would be important

when it comes to making a choice between, for example, a smaller varied meal vs. a larger, low-variety meal. There is some evidence that flavour intensity affects eating satisfaction (McCrickerd & Forde 2016), and an increase in flavour intensity could be readily combined with increased variety. Similarly, altering unit size is compatible with enhancement through increased variety and/or increased flavour intensity. The basis for altering unit size is the observation that for rats and humans, it seems that multiple pieces of a food are perceived as more rewarding than an equicaloric single piece of the same food (Wadhera *et al.* 2012). Remarkably, in one study in humans, it was found that consumption of a bagel cut into quarters reduced subsequent energy intake more than consumption of the same bagel served whole (Wadhera *et al.* 2012; see also Chang *et al.* 2012).

We are just beginning these studies on enhancing the reward value of reduced portion sizes. In a preliminary study, we investigated the effects of reducing the portion size of a sandwich and flapjack lunchtime meal by 25% and 50%. Participants were required to consume all of the meal, either 675, 506 or 338 kcal, and were then presented with 'snack foods', a bowl of chocolate chip cookies and a bowl of salted corn chips, either immediately after the meal or 2½ hours later. They were invited to eat as much of the snack foods as they wanted. The result was that when allowed to eat again immediately after lunch, participants compensated for just over half the lower energy value of the smaller lunches. However, there was almost no compensatory eating after 2½ hours. This is encouraging because it indicates that reduced portion size can be expected to be effective in reducing overall energy intake, providing that further eating can be avoided at the end or soon after the end of the meal.

This result, that is the lack of compensation 2½ hours after consuming a reduced portion size, is consistent with evidence showing decreased energy compensation at longer inter-meal intervals in studies in which the manipulation of energy content of the preceding meal (or 'preload' as it is termed in these studies) is disguised (Almiron-Roig *et al.* 2013). The difference is, of course, that in our study, it was fully evident to participants that they were served smaller portions at lunch on some days. Another study has also found no compensation for reduced portion size when the next eating occasion was delayed (for 4 hours; Lewis *et al.* 2015). These results are fully consistent with the effects of missing breakfast, and together, they point to the fact that after several hours have elapsed, appetite is largely unaffected by how

much is eaten at the last meal, and that includes whether the amount consumed was the usual amount, half that or nothing at all. On the other hand, there is likely to be compensation after a smaller than usual meal if there is an opportunity to eat again soon. Our focus is on how to prevent this through increasing the reward value of the smaller meal (without increasing its energy content), and thus maintain meal satisfaction.

We also plan in our research to investigate possible adaptation to reduced portion sizes. For example, can variety continue to compensate for fewer calories, or does satisfaction decline and compensatory eating increase with repeated exposure to a smaller portion, whether enhanced or not? Promisingly, there is evidence that satiety adapts in line with the size of meal consumed (Geliebter & Hashim 2001; Geliebter *et al.* 2004), so that the fullness felt from a smaller meal might increase over time.

Finally, another line of enquiry related to these studies is to investigate the 'natural' variation in reward value of commonly eaten foods. Akin to Holt *et al.*'s (1995) satiety index, our interest is in identifying foods that have a high reward value per calorie (Reward Index), on the basis that favouring such foods should increase meal satisfaction (per calorie) and, in line with our arguments above, help reduce overall energy intake. Whilst energy content and energy density are major determinants of food reward, consistent with our studies we predict that other features, such as variety and flavour intensity, will also contribute significantly. Additionally, we expect to find that sweetness is important for food reward, as sweet taste is innately rewarding (Steiner *et al.* 2001). That being so, using low-calorie sweeteners to replace sugar in foods and drinks ought to substantially offset the loss of reward value due to the reduction in energy content. This may well be a good part of the reason that low-calorie sweeteners aid weight management (Rogers *et al.* 2016).

Summary and conclusions

Our thesis is that neither eating more nor eating less than is required to maintain energy balance is strongly resisted by our physiology (Rogers & Brunstrom 2016). Nonetheless, trying to eat less in a food-rich environment is difficult because eating is inherently pleasurable. We suggest that modifications to that environment, including reducing food portion size [and reducing food energy density (Rogers & Brunstrom 2016)], are needed to help reduce energy intake.

By enhancing certain qualities of the food on offer (including variety, flavour and presentation), this could be done without compromising eating pleasure. Individually, recognising that, for example, missing an occasional meal does not compromise mental or physical functioning, or lead to subsequent overeating (the evidence is that compensatory eating is minimal), should be helpful in the goal of eating less. Professional advice (*e.g.* NHS Choices www.nhs.uk/Livewell/loseweight/Pages/Healthybreakfasts.aspx) should be updated to reflect these findings, and more generally, we advocate reframing the challenges of healthy weight management to be consistent with the biological reality of appetite and weight control.

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